Rhodium(III)-Catalyzed Heterocycle Synthesis Using an Internal Oxidant: Improved Reactivity and Mechanistic Studies

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ABSTRACT: Directing groups that can act as internal oxidants have recently been shown to be beneficial in metal-catalyzed heterocycle syntheses that undergo C–H functionalization. Pursuant to the rhodium(III)-catalyzed redox-neutral isoquinolone synthesis that we recently reported, we present in this article the development of a more reactive internal oxidant/directing group that can promote the formation of a wide variety of isoquinolones at room temperature while employing low catalyst loadings (0.5 mol %). In contrast to previously reported oxidative rhodium(III)-catalyzed heterocycle syntheses, the new conditions allow for the first time the use of terminal alkynes. Also, it is shown that the use of alkynes, instead of alkenes, leads to the room temperature formation of 3,4-dihydroisoquinolones. Mechanistic investigations of this new system point to a change in the turnover limiting step of the catalytic cycle relative to the previously reported conditions. Concerted metalation—deprotonation (CMD) is now proposed to be the turnover limiting step. In addition, DFT calculations conducted on this system agree with a stepwise C–N bond reductive elimination/N–O bond oxidative addition mechanism to afford the desired heterocycle. Concepts highlighted by the calculations were found to be consistent with experimental results.

INTRODUCTION

The wealth of nitrogen-containing heterocycles in biologically active molecules has provided a driving force for chemists to develop increasingly efficient methods toward their synthesis. While the construction of many heterocyclic molecules traditionally required harsh conditions, transition metal catalysis has provided advantageous alternatives. Indeed, recently developed methods now allow for mild, functional group tolerant and high yielding syntheses of several types of valuable heterocyclic compounds. Intermolecular methods involving palladium-catalyzed oxidative addition/reductive elimination steps constitute outstanding examples as they provide an effective approach to a wide variety of heterocycles through instinctive bond disconnections. Pioneering work from Larock is illustrative, wherein a substrate containing both a nitrogen-containing moiety and a carbon-halide bond can undergo annulation with an alkyne (Scheme 1). Although these protocols have proved to be effective, as demonstrated by their utilization in medicinal chemistry and natural product syntheses, they are limited by the availability of the preactivated substrates, which can be expensive or nontrivial to prepare.

To address this drawback, our group and others have recently focused on exploiting a C–H bond under oxidative conditions in place of a C–X bond, which allows the use of easily accessible starting materials. The strategy typically makes use of the nitrogen-containing moiety as a directing group to effect cyclometalation at the C–H bond. Then, insertion of an alkyne can be followed by C–N bond reductive elimination to yield the desired heterocycle. Cp*Rh(III)Ln were found to be competent catalysts for these transformations. As a result, within the last three years, methods to synthesize indoles, isoquinolines, isoquinolones, pyrroles, and pyridones have been developed. One common feature of all these reactions is the requisite use of internal alkynes, which give rise exclusively to disubstituted heterocycles. This limitation stems from the use of Cu(OAc)2·H2O as oxidant to turnover the rhodium catalyst. Dimerization occurs preferentially when terminal alkynes are employed, preventing the monosubstituted heterocycle from being formed.

Scheme 1. Heterocycle formation through Cross-Coupling/Cyclization

Conventional Preactivation Strategy

Oxidative Strategy

Redox-Neutral Strategy (This work)

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In recent elegant reports, Satoh and Miura, Glorius, and Bergman and Ellman independently demonstrated that using alkenes under very similar conditions resulted in oxidative olefination reaction. These reactions demonstrate the capability of Rh(III) catalysts to insert into alkenes and then β-hydride eliminate. However, reports on the use of alkenes to form saturated heterocycles via C(sp^3)−N bond reductive elimination remain rare.

We have recently reported the synthesis of isoquinolones from benzamide-type starting materials (Scheme 2). Our initial strategy was to employ a hydroxamic acid as a strong directing group to effect the ortho metalation. Yu has pioneered their use as a directing group with various palladium-catalyzed C−H functionalization reactions. Interestingly, we realized that when employing this directing group, no external oxidant was needed to turn over the rhodium catalyst and yield the desired isoquinolone. The N−O bond contained in the substrate was cleaved during the reaction and found to obviate the need for an external oxidant, which is an emerging concept that has been employed very recently in the context of a palladium-catalyzed C−H functionalizations by Hartwig and Cui and Wu. Since this isoquinolone synthesis does not require copper additives, we surmised that further development of the method could address some of the alkyne related limitations previously mentioned.

In this article, we describe (1) the optimization of the internal oxidant/directing group leading to the discovery of increased reactivity which allows heterocycle formation to be performed at room temperature using low catalyst loading; (2) the expanded scope of the reaction which now enables the use of terminal alkynes and alkenes, the former yielding monosubstituted isoquinolones and the later giving saturated heterocycles while furnishing C(sp^3)−N bonds; (3) computational and experimental studies which reveal important insights about the mechanism of the redox-neutral rhodium-catalyzed isoquinolone formation; and (4) the application of these findings to the synthesis of isoquinolines.

RESULT AND DISCUSSION

Internal Oxidant Optimization. We previously reported an isoquinolone synthesis from the coupling of N-methoxyhydroxamic acids with alkynes. Although the reaction conditions reported were mild, we questioned whether it would be possible to achieve better reactivity by modifying the nature of the built-in oxidant. We reasoned that using hydroxamic acids bearing better leaving groups, or groups that could better stabilize intermediates of the catalytic cycle (Figure 1), would be beneficial to the reaction.

With this mind set, a variety of hydroxamic acid-type substrates were synthesized, each one having a different leaving group on the nitrogen. Since the reaction was known to be more challenging with internal alkynes substituted with two alkyl groups, substrate optimization was performed using both diaryl-substituted and dialkyl-substituted alkynes (Chart 1).

Next, we sought to evaluate the improved reactivity provided by the new internal oxidant (Table 1). It was found that, while keeping the temperature at 60 °C, the catalyst loading could be reduced to 0.5 mol % Rh(III) dimer without impacting the yield (Table 1, entry 2). However, lowering the Rh(III) dimer content to 0.5 mol % decreased the yield considerably (Table 1, entry 3). We were then pleased to find that running the reaction at room temperature could also provide nearly quantitative yields while using only 0.5 mol % Rh(III) (Table 1, entry 5). Lowering the catalyst loading to 0.1 mol % at this temperature resulted in an incomplete reaction affording 61% 1H NMR yield after 16 h. Finally, it is noteworthy that the isoquinolone synthesis can be performed on gram-scale using 0.5 mol % Rh(III) to afford 3,4-diphenylisoquinolone in 96% isolated yield (Table 1, entry 7).

Improved Reaction Scope. With the newly found optimal internal oxidant, a reinvestigation of the scope of the isoquinolone synthesis previously reported was carried out. All the experiments were conducted with 0.5 mol % rhodium(III) dimer at room temperature. Chart 2 presents a comparison of the previously reported and newly designed conditions. With diaryl-substituted alkynes, yields remain high with both systems (Chart 2, 3a−c). The electron withdrawing or donating character of the substituents on the hydroxamic acids does not seem to affect the outcome of the reaction. When a meta-substituted starting material is employed, the corresponding isoquinolone is obtained as a single regioisomer (Chart 2, 3d). Moreover, in...
contrast to the first generation system (N-OMe), the use of alkyl-aryl disubstituted alkynes gave high yields and high regioselectivity with the sp$^2$ center being installed at the 3-position of the heterocycle. Interestingly, a TMS-protected alkyne was also tolerated, which constitutes a useful handle for further functionalization (Chart 2, 3h). Additionally, while dialkyl substituted alkynes were problematic with the previously reported

Table 1. Increased Reactivity Provided by the Pivalate Internal Oxidant

<table>
<thead>
<tr>
<th>entry</th>
<th>temperature (°C)</th>
<th>catalyst loading (mol %)</th>
<th>1H NMR yield (%)</th>
</tr>
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<tr>
<td>1</td>
<td>60</td>
<td>2.5</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>0.5</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>0.05</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>rt</td>
<td>2.5</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>rt</td>
<td>0.25</td>
<td>99</td>
</tr>
<tr>
<td>6</td>
<td>rt</td>
<td>0.05</td>
<td>61</td>
</tr>
<tr>
<td>7</td>
<td>rt</td>
<td>0.25</td>
<td>96 (isolated)</td>
</tr>
</tbody>
</table>

Conditions: 1e (1 equiv., 0.20 mmol), 2a (1.1 equiv., 0.22 mmol), CsOAc (2 equiv., 0.40 mmol), [Cp*RhCl$_2$]$_2$ (x mol %), MeOH (0.2 M), specified temperature, 16 h. $^*$1H NMR yield vs trimethoxybenzene as internal standard. $^\dagger$Reaction conducted on a 1.00 g scale of 1e.
conditions, they are now well suited using the pivaloyl group as internal oxidant. When unsymmetrical dialkyl-substituted alkenes are employed, the more sterically demanding group will typically be installed at the 4-position (Chart 2, 3j). This outcome is in agreement with previous reports on rhodium-catalyzed heterocycle formation.

As mentioned earlier, an important limitation encountered with the recently developed rhodium-catalyzed oxidative synthesis of nitrogen-containing heterocycles was the inability to incorporate terminal alkenes. Their use has primarily lead to alkyne dimerization (glaser coupling) due to the Cu(II) oxidant typically employed in these reactions. As a result, only disubstituted heterocycles have been synthesized using Rh(III)-catalyzed methods. With the newly designed copper-free conditions, a reinvestigation of this restraint was conducted. It was found that terminal alkenes were now tolerated and give the desired monosubstituted heterocycle in moderate to high yield. In addition, the regioselectivity of their insertion is highly predictable, with the terminal end being located at the 4-position. As shown in Table 2, with yields ranging from 85% to 95%, the reaction is compatible with alkyl-substituted terminal alkenes. Performing the heterocycle formation at 60 °C also allowed for the formation of a 3-methylester monosubstituted isoquinolone (Table 2, 4c). Moreover, we were pleased to observe that trimethylsilylacetylene is a suitable alkyne yielding an isoquinolone that can be subsequently functionalized (Table 2, 4e). Phenylacetylene was also subjected to the reaction conditions; however, none of the desired product was observed.

With recent reports on oxidative olefination using Cp*Rh-(III)L as catalysts, we were interested in investigating the use of alkenes under our new conditions to access the corresponding 3,4-dihydro heterocycle. The inherent challenge with this method is the formation of the C(sp3)–N bond while avoiding the well-documented β-hydride elimination which gives rise to Heck-type products. To do so, the C–N bond forming/N–O bond cleaving step must be lower in energy than β-hydride elimination. Considering the mild reaction conditions required for the isoquinolone synthesis, we presumed that the formation of the unsaturated heterocycle could occur preferentially. Indeed, it was found that alkenes do undergo insertion followed by C–N bond formation with no product arising from β-hydride elimination. Table 2. Terminal Alkyne Scope

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkyne</th>
<th>Product</th>
<th>Yield</th>
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<tbody>
<tr>
<td>1</td>
<td>n-hex</td>
<td>4a</td>
<td>92%</td>
</tr>
<tr>
<td>2</td>
<td>allyl</td>
<td>4b</td>
<td>85%</td>
</tr>
<tr>
<td>3</td>
<td>acetylene</td>
<td>4c</td>
<td>49%</td>
</tr>
<tr>
<td>4</td>
<td>trimethylsilylacetylene</td>
<td>4d</td>
<td>95%</td>
</tr>
<tr>
<td>5</td>
<td>TMS</td>
<td>4e</td>
<td>75%</td>
</tr>
</tbody>
</table>

Conditions: 1g (1 equiv, 0.2 mmol), 2 (1.1 equiv, 0.22 mmol), CsOAc (2 equiv, 0.40 mmol), [Cp*RhCl2]2 (2.5 mol %), MeOH (0.2 M), room temperature, 16 h. Isolated yields are reported. 0.5 mol % [Cp*RhCl2]2 was employed. Reaction ran at 60 °C.

Scheme 3. Access to unsubstituted isoquinolone via retro Diels-Alder reaction

Table 2. Terminal Alkyne Scope

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<td>acetylene</td>
<td>4c</td>
<td>49%</td>
</tr>
<tr>
<td>4</td>
<td>trimethylsilylacetylene</td>
<td>4d</td>
<td>95%</td>
</tr>
<tr>
<td>5</td>
<td>TMS</td>
<td>4e</td>
<td>75%</td>
</tr>
</tbody>
</table>

Conditions: 1g (1 equiv, 0.20 mmol), 2 (1.1 equiv, 0.22 mmol), CsOAc (2 equiv, 0.40 mmol), [Cp*RhCl2]2 (2.5 mol %), MeOH (0.2 M), room temperature, 16 h. Isolated yields are reported. 0.5 mol % [Cp*RhCl2]2 was employed. Reaction ran at 60 °C.

Scheme 3. Access to unsubstituted isoquinolone via retro Diels-Alder reaction

Computational and Experimental Mechanistic Investigations. The observed increase in reactivity provided by the O-pivaloyloxydrazinic acid directing group/internal oxidant as well as the uncertain nature of the C–N bond forming/N–O bond cleaving step of the catalytic cycle prompted us to further investigate the mechanism of this transformation. We determined in our previous communications on the subject that the first step of the catalytic cycle was likely a reversible aren rhodation.15 We proposed that alkene insertion was then occurring, which was followed by a concerted or stepwise C–N bond forming/N–O bond cleaving step. It was also demonstrated from crossover experiments that the N–O bond cleavage happened in an intramolecular sense (Scheme 4). From to construct, in a minimal amount of steps, a wide variety isoquinolones having various substitution patterns while generating only pivalic acid as a byproduct.
this last piece of information, we reasoned that two mechanistic pathways could account for the last steps of the catalytic cycle (Figure 2). Pathway A consists of a concerted process where a highly organized six-membered cyclic transition state accounts for simultaneous C\(\equiv\)C/N bond formation and N/C=O bond cleavage. The main characteristic of such a mechanism is that the Rh(III) catalyst remains at the +3 oxidation state throughout the entire catalytic cycle. Pathway B is a more common reductive elimination/oxidative addition process that would occur in a stepwise fashion. The C\(\equiv\)C/N bond reductive elimination would yield an intermediate that would readily proceed to N/C=O bond oxidative addition. For such a mechanism to be operative and consistent with the experimental data,\textsuperscript{15} the oxidative addition would have to occur faster than decoordination of the substrate from the catalyst.

Drawing inspiration from the work of Rovis on a similar system,\textsuperscript{6h} a reaction was conducted to establish the reversibility of the cyclometalation in the presence of an alkyne (Scheme 5). Thus, the reaction of 1a with 2a using the standard reaction conditions in deuterated methanol was stopped before completion. Compounds 1a and 3a were isolated and their deuterium content was analyzed by \(^1\)H NMR. With both recovered compounds, no deuterium incorporation was observed suggesting that cyclometalation is irreversible in presence of 2a.

From this point, we were intrigued to determine the turnover limiting step of the catalytic cycle. Taking into account the new system’s reactivity, it was also appropriate to determine whether

\textbf{Table 3. Alkene Scope}\textsuperscript{a}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkene</th>
<th>Product</th>
<th>Yield\textsuperscript{d}</th>
<th>Regioselectivity</th>
<th>Entry</th>
<th>Alkene</th>
<th>Product</th>
<th>Yield\textsuperscript{d}</th>
<th>Regioselectivity</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Ph</td>
<td>6a</td>
<td>90%</td>
<td>&gt;20:1</td>
<td>5</td>
<td>Ph</td>
<td>6e</td>
<td>85%</td>
<td>~1.3:1</td>
</tr>
<tr>
<td>2</td>
<td>Ph</td>
<td>6b</td>
<td>77%</td>
<td>&gt;20:1</td>
<td>6</td>
<td>Ph</td>
<td>6f</td>
<td>85%</td>
<td>2:1</td>
</tr>
<tr>
<td>3</td>
<td>Ph</td>
<td>6c</td>
<td>91%</td>
<td>N/A</td>
<td>7</td>
<td>Ph</td>
<td>6g</td>
<td>95%</td>
<td>1:4.5\textsuperscript{d}</td>
</tr>
<tr>
<td>4</td>
<td>Ph</td>
<td>6d</td>
<td>77%</td>
<td>&gt;20:1</td>
<td>8</td>
<td>(balloon)</td>
<td>6h</td>
<td>95%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Conditions: 1e (1.0 equiv, 0.20 mmol), 5 (1.1 equiv, 0.22 mmol), CsOAc (2.0 equiv, 0.40 mmol), [Cp*RhCl\(_2\)]\(_2\) (0.5 mol %), MeOH (0.2 M), room temperature, 16 h. \textsuperscript{b} Isolated yields are reported. \textsuperscript{c} Isolated yield of both regioisomers. \textsuperscript{d} Inseparable mixture of regioisomer.
To acquire a better understanding of the overall catalytic cycle, quantum chemical calculations were performed in both the gas phase and with a solvent correction for methanol at 298 K (please refer to Supporting Information for full computational details). The goal of this exercise was to gain insight into the currently unknown nature of the C–N bond forming/N–O bond cleaving event. Scheme 8 presents the relative Gibbs free energy for all the intermediates and transition states, while Scheme 9 shows the resultant catalytic cycle.

**Scheme 6. DKIE Mesurements**

The catalytic cycle starts from CpRh(OAc)₂ (1), which is first coordinated to 1d with concomitant loss of acetic acid. Next, based on mechanistic investigations of closely related systems, and our large primary DKIE, we assumed that C–H bond cleavage would occur via a concerted metalation–deprotonation (CMD) transition state (TS). This step affords intermediate III, where acetic acid is still bound to rhodium. The Gibbs free energy of the CMD TS is 20.5 kcal mol⁻¹, which is the highest barrier reached in the catalytic cycle. Calculations were also conducted with nonprotonated 1d bound to Rh(III) prior to the CMD step. However, a high CMD TS energy of 34.7 kcal mol⁻¹ (Scheme 8, red line) was found with this cationic complex for the CMD process. This pathway was consequently ruled out. This calculation however reveals the importance of substrate deprotonation for allowing a low-barrier catalytic cycle. Continuing with the lowest energy pathway, the acetic acid ligand dissociates from intermediate III to give intermediate IV and then acetylene coordinates to Rh(III) to yield intermediate V. From this point, insertion of acetylene in the Rh–C bond can occur to give intermediate VI, a process where the TS energy is 11.4 kcal mol⁻¹. Then, reductive elimination via TS3 (ΔG° is −0.2 kcal mol⁻¹) allows the C–N bond formation and delivers intermediate VII. The low barrier energy for the reductive elimination step would explain its kinetic irrelevance under the new reaction conditions. Subsequently, a fast oxidative addition occurs via TS4 to form intermediate VIII, which is finally protonated by acetic acid. This last step yields the desired isoquinolone and regenerates the catalyst. Calculations were also attempted to find the lowest energy pathway of a concerted process analogous to pathway A presented in Figure 2, but no low energy pathway was found to match the experimental data. Consequently, we propose pathway B as being operative in the catalytic cycle. The low energy barrier calculated for the N–O bond oxidative addition correlates well with the

**Scheme 7. Rate Measurements for Subtrates with a Different Internal Oxidant**

The slow step is the same with both 1a and 1e. To do so, we conducted deuterium kinetic isotope effect (DKIE) measurements by comparing the initial rates of both systems side by side. Scheme 6 summarizes the results of this study. No DKIE was observed with the N-methoxybenzamide substrate, whereas a large primary DKIE of 15 ± 1 was found with the 1e. These results suggest that the rate-limiting step depends on the internal oxidant. With 1a, the rate-limiting step remains uncertain, whereas the use of 1e makes the C–H bond cleavage the slow step. The high DKIE of 15 ± 1 with 1e can be explained by tunneling effects.

To corroborate this finding, a rate study of the reaction of 1e and 1f with 2c using the new conditions was conducted (Scheme 7). It was found that while the leaving group ability of benzoate is greater than that of pivalate, the reaction occurred 1.7 times faster with the latter. If the N–O bond cleavage was the turnover limiting step, one would expect the substituent with better leaving group ability to react faster. In this case, since the slow step is the same with both systems, one would expect the substituent with the pivalate to be faster as it is the most likely the stronger directing group.

To acquire a better understanding of the overall catalytic cycle, density functional theory (DFT) calculations were conducted for the reaction of substrate 1d (N-OAc) with acetylene using CpRh(OAc)₂ as catalyst. These chemical species were selected to simplify calculations while keeping the essential features of the catalytic cycle as accurate as possible. All computations were performed using the hybrid B3LYP level functional with a TZVP basis set for all atoms except rhodium, for which a DZVP basis set was used. Gibbs
Experimental evidence showing that the cleavage of the N–O bond happens intramolecularly on the substrate on which the C–N bond is formed. It is also of note that a cationic pathway, where the substrate’s directing group is not deprotonated (acting as an L ligand), is considerably higher in energy than a similar pathway where the complex is neutral. Isoquinoline Synthesis. With the development of a mild and robust redox-neutral isoquinoline synthesis, we sought to elaborate on this strategy in order to make it compatible with other heterocycle syntheses. Possessing a somewhat similar structure, we targeted the isoquinoline motif as a potential candidate. Although an excellent communication from Chiba recently reported this extension (Scheme 10),

we were curious to see if the preference for a neutral complex, that is, a complex where the substrate’s directing group acts as an X ligand on rhodium throughout the catalytic cycle, was still valid in this system. A series of experiments were conducted to test this hypothesis.

From the outset, we reacted 7a with 2a under conditions very similar to the ones we initially developed for the isoquinolone synthesis. The thought behind using 7a as starting material was to have weakly acidic protons on the methyl alpha to the oxime moiety. Thus, deprotonation would provide a neutral Rh(III) complex throughout the catalytic cycle. From this experiment, we were pleased to observe that 8a was formed in an 11% 1H NMR yield. Changing the base from CsOAc to the stronger K2CO3 increased the yield of 8a to 86% (Scheme 11, eq 1).

Next, 7a was reacted with the more challenging alkyne 2b using K2CO3 as base (Scheme 11, eq 2). This time, a lower yield of 45% was obtained. Trying to improve this moderate yield, we embarked on the screening of other internal oxidants. Interestingly, when O-mesityloylacetonaphthonoxime (7b) was employed as starting material, a further investigation of the crude reaction mixture’s 1H NMR spectrum revealed that an almost quantitative amount of ester 9 was produced (Scheme 12). If the reaction would proceed as expected, the corresponding benzoate should be observed in place of the methyl ester. The only way a quantitative amount of ester 9 can be produced is by basic methanolysis of 7b, which would concomitantly afford the free acetophenone oxime. This interesting finding led us to question whether the simple free oxime could be the actual competent starting material in these isoquinolines syntheses. Thus, oxime 7c was reacted with 2a and 2b in the standard reaction conditions (Scheme 12, eqs 2 and 3). The 1H NMR yields obtained were found to be essentially the same as the ones obtained using the acyl protected oximes. This finding confirms that the free oxime is the active starting material. It should consequently simplify the preparation of the substrates undergoing this type of reaction.

Scheme 8. Free Energy Diagram (ΔG298K kcal·mol⁻¹ in Methanol) for the Relevant Intermediates, Transition States and Products for the Reaction of 1d with Acetylene

Scheme 9. DFT Calculated Catalytic Cycle

Scheme 10. Chiba’s Work with Isoquinolines

Scheme 11. Base Effect in Isoquinoline Synthesis
Control experiments were then conducted to verify whether deprotonation of the starting material to obtain a neutral Rh(III) complex was indeed important with this system and, if so, to reveal where the deprotonation occurs. Thus, oxime 10 was first reacted with 2a in the standard reaction conditions (Scheme 13, eq 1). A 1H NMR yield of 84% was obtained for this reaction, indicating that, in contrast with our initial assumption, deprotonation alpha to the oxime was not essential to undergo the desired transformation. Subsequently, a reaction of O-methyloxime 7d with 2a was run (Scheme 13, eq 2). From this experiment, no desired isoquinoline was observed. These results are consistent with deprotonation of the oxime oxygen as an important step in the reaction. These findings are also in good agreement with the computational experiments done on the isoquinolone system where it was shown that a deprotonated substrate bound to rhodium lowers the energy barriers of the CMD TS by providing a neutral Rh(III) complex.

**Acknowledgment**

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(34) The structural features of this TS (the C–H and O–H distances for the proton transfer are 1.30 and 1.36 Å, respectively, and the Rh–C distance is 2.23 Å) are fairly similar to those reported in Pd(II)-catalyzed CMD TS structures (the C–H and O–H distances for the proton transfer are 1.44 and 1.21 Å, respectively, and the Pd–C distance is 2.25 Å for the CMD TS for the reaction of C6H5H with [Pd([PtC]Ph)(OAc)] (ref 33e).}